THE CYGNUS X REGION - A MULTI WAVELENGTH VIEW

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The Cygnus X region is one of the most nearby massive star forming regions within our Galaxy, recognised by prominent emission throughout the entire electromagnetic spectrum, from radio to gamma-ray waves. This paper reviews our current knowledge about this region by describing its multi-wavelength characteristics. Particular emphasis will be given to the central stellar cluster Cyg OB2 that dominates the energetics and kinematics in the area. The cluster is also believed to be an active site of nucleosynthesis, as traced by the observation of the 1809 keV gamma-ray line, attributed to radioactive decay of ^{26}Al. New observations obtained by the SPI telescope onboard the INTEGRAL gamma-ray observatory will be presented that corroborate this hypothesis, and that for the first time allow to measure the kinematics of the gas in the hot Cygnus X superbubble.

Keywords: H II regions – ISM: bubbles – Open clusters and associations: Cyg OB2 – nucleosynthesis

1 Introduction

Massive star forming regions are impressive building blocks of active galaxies. They provide large amounts of UV photons leading to the ionisation of the interstellar medium (ISM), observable in the radio and microwave domains, and visible through Hα recombination line emission. They are important sources of interstellar dust heating, leading to ubiquitous infrared emission. The strong winds of their massive stars and the subsequent supernova explosions release considerable amounts of kinetic energy, creating a rarified hot ($\sim 10^6$ K) superbubble emitting in the X-ray domain; its cavity may eventually be discerned from H I and CO observations of interstellar gas. Massive star forming regions are potential sources of cosmic-ray particle acceleration, observable by radio synchrotron emission and high-energy gamma-ray emission. Their massive stars synthesize considerable amounts of fresh heavy nuclei that are released either by the stellar winds or the subsequent supernova explosions, and that contribute to the chemical enrichment

of the host galaxy. Nucleosynthesis products may be traced by co-produced radioactive isotopes that are observable through their characteristic gamma-ray line emission.

Studying massive star forming regions in a single waveband provides certainly interesting clues on their characteristics; yet a comprehensive understanding of the phenomenon requires a rigorous multi-wavelength approach. I present in this paper a multi-wavelength view of the Cygnus X region, one of the most nearby galactic massive star forming regions, at a distance of ~ 1.4 kpc. Cygnus X lies in the galactic plane at longitudes $\sim 80°$, making it a fairly well isolated source on the sky. Yet, foreground dust obscuration produces substantial extinction of parts of the region, preventing thus a comprehensive survey in the visible and soft X-ray bands. Eventually, a spiral arm structure seen tangentially over distances $\sim 1-4$ kpc may also be present in this area of the sky, yet highly uncertain distance estimates make it difficult to assess the reality of this feature. In any case, most massive stars in Cygnus X, and in particular the young massive cluster Cyg OB2, are situated at about the same distance (~ 1.4 kpc), suggesting a physical relation of the objects in the region.

The proximity of Cygnus X and its isolation from the galactic ridge makes it a brilliant test case for understanding massive star forming regions. Cygnus X is like a *Rosetta stone* of massive star formation, enabling a profound understanding of the various processes at work and of their interplay.

2 Cygnus OB2

Cyg OB2, originally classified as OB association, is one of the most massive star clusters known in our Galaxy. It is situated at galactic coordinates $(l, b) \sim (80°, 1°)$ with an angular diameter of 2° (50 pc at the distance of Cyg OB2), right at the heart of the Cygnus X region.[16] Foreground dust obscuration sheds parts of the cluster in the visible waveband, requiring infrared observations for a complete census. Such a census has been obtained using the 2MASS survey, which revealed a total of 120 ± 20 O star members and suggests a total cluster mass of $(4-10) \times 10^4\ M_\odot$.[16] A synthetic plot of the stellar distribution in the area is shown in Fig. 1.

Near-infrared spectroscopic observations support these findings.[6,12] Distance estimates to Cyg OB2 were generally situated around 1.7 kpc, yet the recent revision of the O-star effective temperature scale suggest a smaller value of 1.4 kpc.[12] The cluster age has been estimated from isochrone fitting to $3-4$ Myr[15], where the age range may reflect a non-coeval star forming event. The total Lyman continuum luminosity of the stars has been estimated to 10^{51} ph s^{-1}, their mechanical luminosity amounts to a few 10^{39} erg s^{-1}.[15,18] Obviously, with such high luminosities, Cyg OB2 should leave a clear imprint on the interstellar surroundings.

Cyg OB2 houses some of the hottest and most luminous stars known in our Galaxy. Among the members is a O3 If* star, three Wolf-Rayet stars, and two LBV candidates. Since spectroscopic measurements are still incomplete for the cluster, these numbers present probably lower limits to the population of extremely massive and evolved objects.

3 The Cygnus X region

3.1 Radio emission

The Cygnus X region has been named by Piddington & Minnett (1952) who were the first to observe an extended source of radio emission in the constellation of Cygnus. Cygnus X is composed of numerous individual H II regions[9] with distances estimated between $1.2-2.4$ kpc.[8] In addition to these point-like sources, a component of diffuse thermal radio emission has been identified that constitutes $\gtrsim 50\%$ of the emission in Cygnus X.[24]

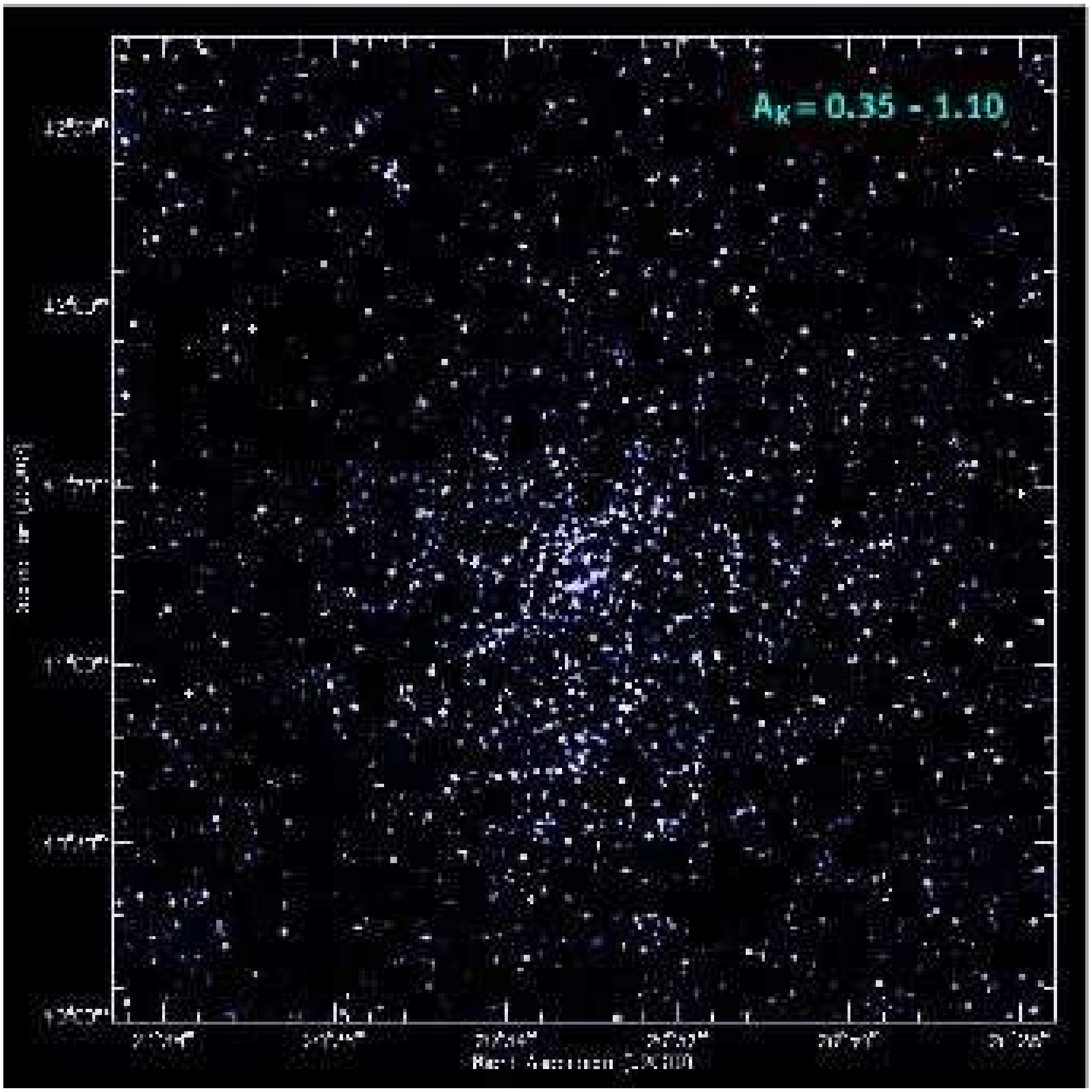

Figure 1: Synthetic absorption free plot of the stellar density distribution in the Cyg OB2 area based on 2MASS data. Stars in the absorption band $A_K = 0.35 - 1.1$ mag are shown as symbols with brightness proportional to the absolute (reddening corrected) K band magnitude.

Figure 2 presents a two-colour radio image of the region. Thermal emission appears blueish while non-thermal (i.e. synchrotron emission) appears reddish in this representation. The dominance of thermal emission is obvious, as well as the presence of ubiquitous diffuse emission with embedded compact and ultra-compact H II regions. Only little synchrotron emission is present, such as the circular feature near $(l, b) \sim (78°, 2°)$ which corresponds to the γ Cygni supernova remnant. Apparently, the radio emission originates mainly from the ionisation of the interstellar medium; the supernova activity seems rather low. These facts suggest that the Cygnus X region is very young, probably not older than 4 Myr.[15]

Véron (1965) has suggested that Cygnus X is a single giant H II region powered by Cyg OB2, yet the identification of individual H II regions with their exciting stars in Cygnus X indicates that there are also other ionising sources in the area. About 50% of the ionising luminosity in Cygnus X comes from Cyg OB2, the rest is provided by massive stars that are found in the surrounding associations and clusters.[15] Using typical values for electron temperature and density of H II regions (T_e = 6000 K and n_e = 10 cm^{-3}, respectively), the ionising power

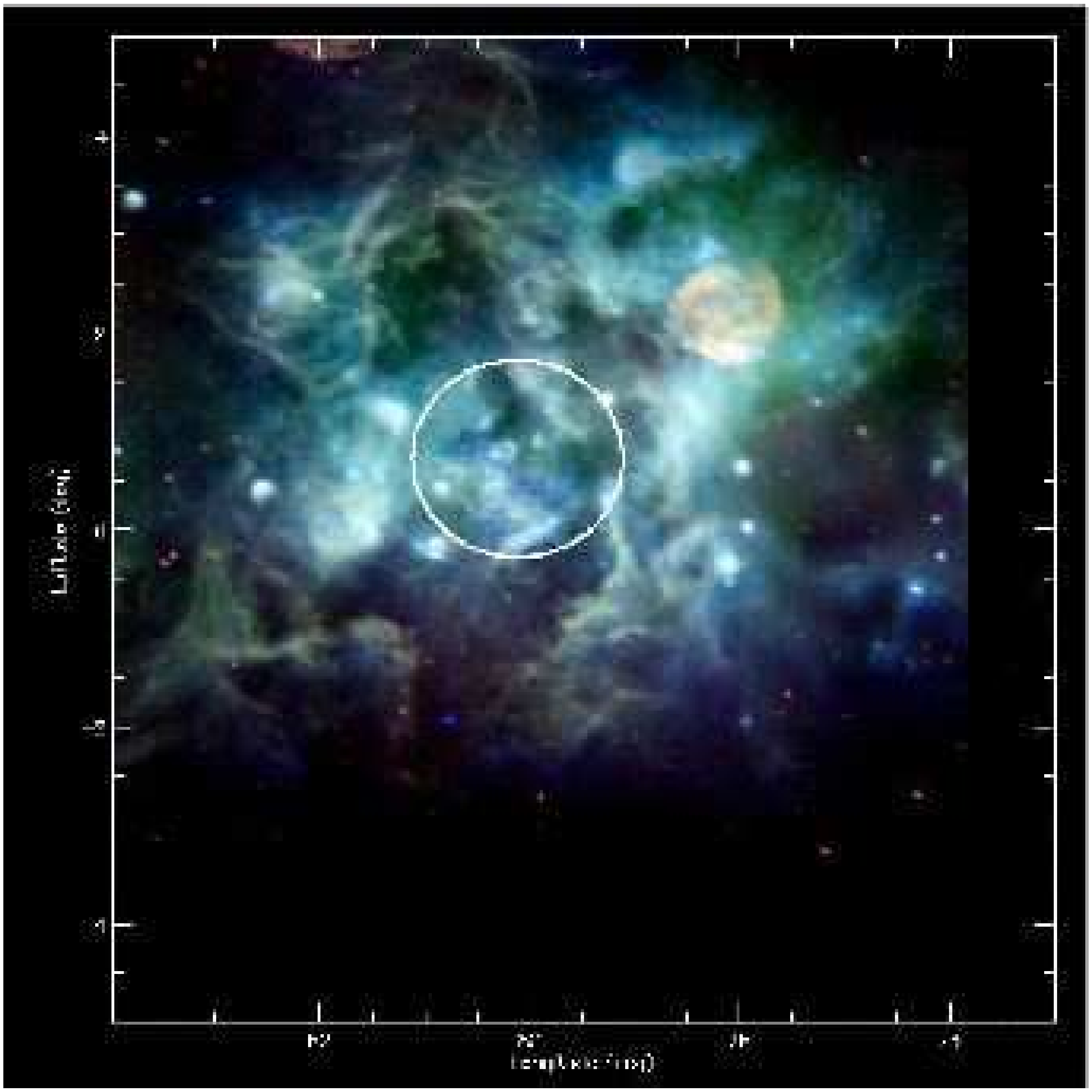

Figure 2: DRAO 74 cm (red) and 21 cm (blue) composite of radio emission from the Cygnus X region. Thermal emission appears blueish while non-thermal (i.e. synchrotron emission) appears reddish in this representation. The Cyg OB2 association, represented by the white circle, is located near the centre of the Cygnus X region.

of Cyg OB2 alone would lead to a Strömgren sphere of 60 pc in radius, corresponding to an angular diameter of 5° at the distance of the cluster. This diameter is in good agreement with the observed extent of the diffuse thermal radio component in Cygnus X, supporting the idea that this emission component represents a giant H II region that is powered by Cyg OB2.

3.2 Infrared emission

The mid- and far-infrared image of Cygnus X shows striking similarities with the radio emission: a diffuse emission structure with embedded point-like sources (cf. Fig. 3). The infrared spectrum becomes harder (as illustrated by the blueish colour) towards the centre of Cygnus X, probably as a result of dust heating by the massive stars of the embedded Cyg OB2 association. Around Cyg OB2, a large number of point-like sources is detected, that have been identified as either embedded early-type stars or star clusters, or young stellar objects (YSO).[19] Many of them are associated to the compact and ultra-compact H II regions that are observed in thermal radio

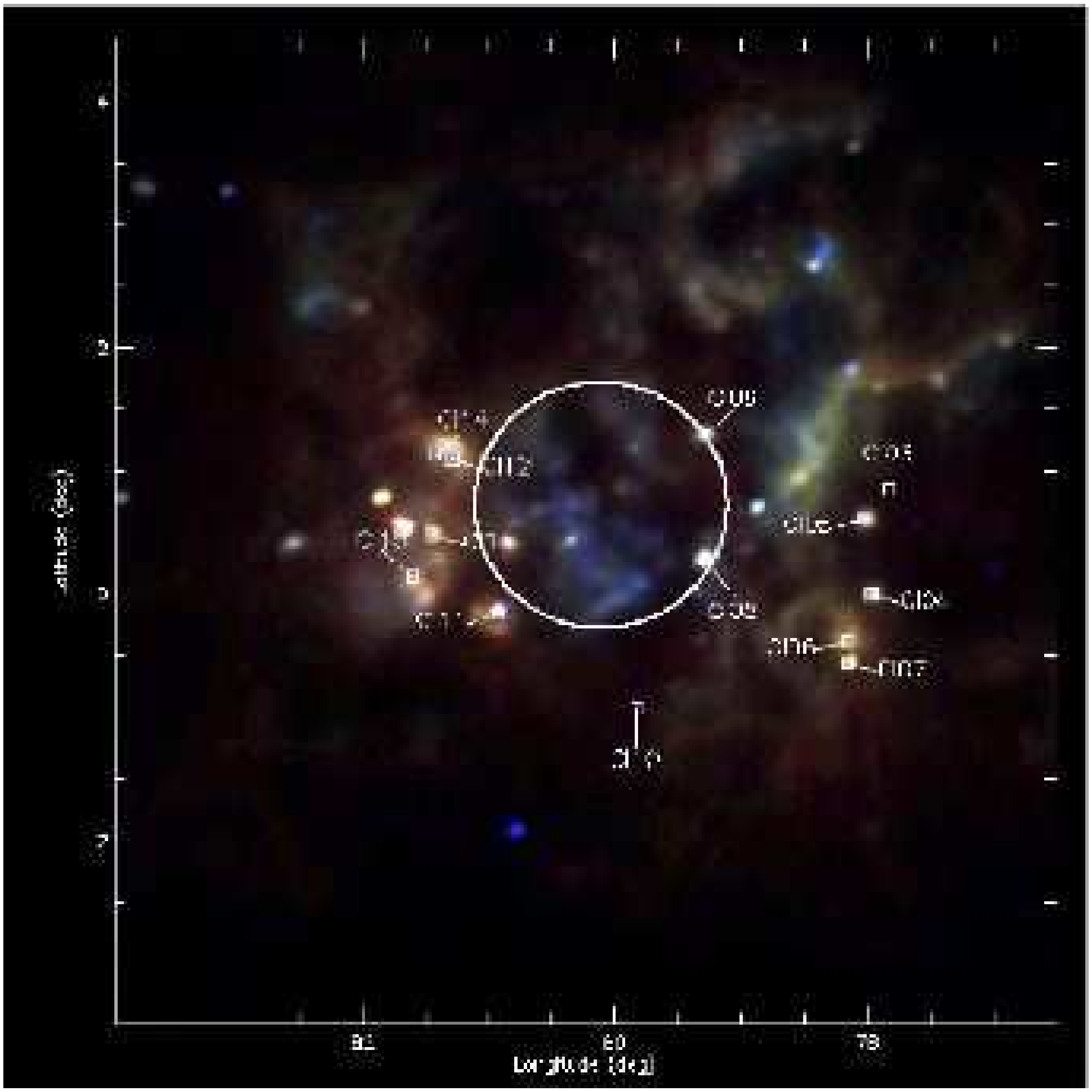

Figure 3: IRAS three-colour composite of the Cygnus X region (red: 100 μm, yellow: 60 μm, blue: 25 μm). The central region, heated by the Cyg OB2 cluster appears blue, while the surrounding colder medium shows up as reddish emission. Bright spots coincide generally with embedded star clusters (labelled according to the catalogue of embedded star clusters given by Le Duigou & Knödlseder, 2002).

continuum emission.

Le Duigou & Knödlseder (2002) have searched 2MASS near-infrared data for possible embedded star clusters in the area and found 15 such objects. Although no detailed age information is available for these objects, their embedded nature suggests a fairly small age ($\sim$ 1Myr). In addition, their location at the outskirts of Cyg OB2 indicates a triggered star formation event, as result of the expansion of a superbubble around Cyg OB2 that has compressed the ambient ISM.

Such a superbubble has been searched for by several authors in interstellar gas maps of the region (H I and CO)[14,13,10,18], yet velocity crowding makes the identification of interstellar bubbles difficult in the Cygnus area. Assuming that the Cyg OB2 association injects kinetic energy into the ISM since $\sim$ 2 Myr, and assuming an initial density of 100 cm^{-3} (in agreement with measurements of immersed molecular clumps in Cyg OB2)[11], a superbubble with a radius of 63 pc should have been created by the association, with an actual bubble shell velocity of 19

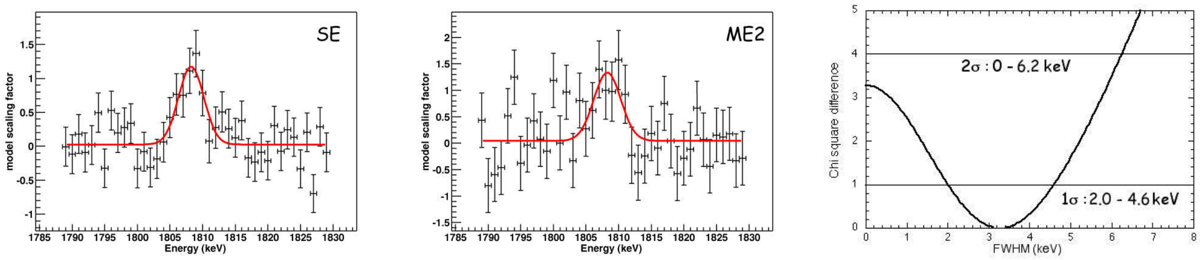

Figure 4: 1809 keV gamma-ray line emission spectra obtained from observations using the SPI telescope aboard the INTEGRAL gamma-ray observatory. The left panel shows the spectrum for single-detector events (SE), the mid panel shows the spectrum for double-detector events (ME2) (SE and ME2 refer to two different event types that are registered by the SPI telescope; the detection of the signal at the same level in both event types is a valuable internal consistency check of the complex data analysis; the information of both event types is added to achieve the maximum sensitivity of the SPI telescope). The right panel illustrates the χ^2 statistics of a gaussian shaped line profile fit as function of the astrophysical line width. At the 1σ level, a line broadening of 3.3 ± 1.3 keV (FWHM) is suggested by the data, while the line is compatible with an unbroadened line at the 2σ level.

km s^{-1}.[18] At the distance of Cyg OB2, the superbubble should have an apparent diameter of 5°, comparable to the estimated size of the Strömgren sphere, and comparable to the location of the embedded star clusters that may have formed in the compressed ISM surrounding the bubble.

3.3 The Cygnus X-ray superbubble

The Cygnus X-ray superbubble has been discovered by Cash et al. (1980) as an incomplete ring of soft X-ray emission $13° \times 18°$ in diameter surrounding the Cygnus X region. The morphology of the X-ray emission is shaped by heavy foreground extinction due to the Great Cygnus Rift, and the underlying source could in reality present a nearly uniform emission morphology.[5,22] The origin of the Cygnus X-ray superbubble is still subject to debate, and the protagonists split into two groups who either suggest a single superbubble formed by Cyg OB2[5,1] or a superposition of sources aligned along the local spiral arm.[4,22] Probably, the truth lies between these extreme positions: a substantial fraction of the X-ray emission may indeed arise from shock heating due to the combined stellar winds of Cyg OB2, while other objects along the line of sight my also contribute to the emission.

3.4 Gamma-ray emission from Cygnus X

Prominent 1809 keV gamma-ray line emission has been reported from the Cygnus X region based on observations of the COMPTEL telescope.[7,21] The 1809 keV gamma-ray line arises from the decay of ^{26}Al, a radioactive isotope with a mean lifetime of about one million years. ^{26}Al is mainly produced during the core hydrogen burning phase in massive stars, and is subsequently ejected by stellar winds (in particular during the LBV and Wolf-Rayet phases) and/or supernova explosions. The presence of ^{26}Al in the Cygnus region is again a clear indicator of extensive mass loss by massive ($M > 20 M_{\odot}$) stars in this area.

The recently launched INTEGRAL gamma-ray observatory, equipped with the high-resolution gamma-ray spectrometer SPI, observed the Cygnus X region during the performance verification phase end of 2002. Figure 4 shows the spectra that have been obtained. The flux integrated over the area $l = [73°, 93°]$ and $b = [-7°, 7°]$ in the line amounts to $(7.2 \pm 1.8) \times 10^{-5}$ ph cm^{-2}s^{-1}. The energy of the line is measured to 1808.4 ± 0.3 keV, compatible with the ^{26}Al decay energy of 1808.65 keV. The line appears broadened, with a gaussian FWHM of 3.3 ± 1.3 keV, yet the statistical confidence of this measurement is still relatively modest.

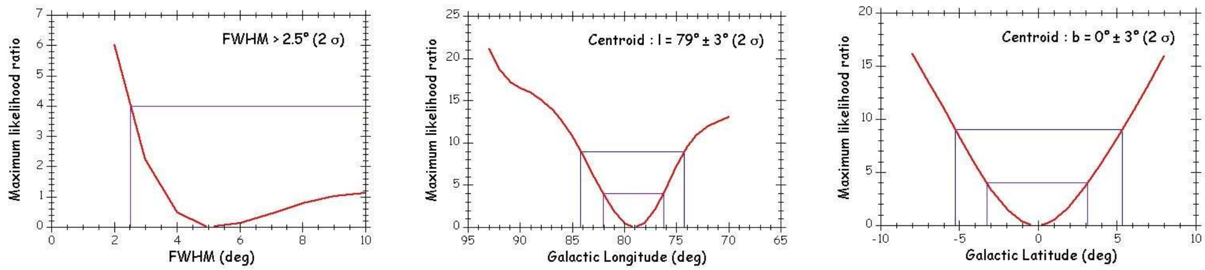

Figure 5: Morphology constraints on the distribution of 1809 keV gamma-ray line emission in Cygnus X, obtained from SPI/INTEGRAL data using the Maximum Likelihood Ratio test (MLR). The left panel illustrates the dependence of the MLR as function on the extension of the emission, assuming a 2d-gaussian shaped intensity distribution centred on galactic longitude/latitude of $80^\circ/0^\circ$ (the abscissa shows the FWHM of the 2d-gaussian). The source is extended by more than 2.5° at the 2σ significance level, an optimum extension of 5° is suggested. The mid panel show the dependence of the MLR on galactic longitude, assuming a 2d-gaussian shaped intensity distribution of FWHM$= 5^\circ$ at galactic latitudes of 0°. The emission is located at galactic longitude $79^\circ \pm 3^\circ$ (2σ confidence level). The right panel show the dependence of the MLR on galactic latitude, assuming a 2d-gaussian shaped intensity distribution of FWHM$= 5^\circ$ at galactic longitude of 79°. The emission is located in the galactic plane at latitude $0^\circ \pm 3^\circ$ (2σ confidence level). 2σ and 3σ confidence limits are indicated as violet and blue lines, respectively.

SPI provided also valuable information on the morphology of the 1809 keV emission. Figure 5 illustrates that the emission is extended, with a most likely value of 5° FWHM assuming a gaussian shaped emission. The emission is located at galactic longitude $79^\circ \pm 3^\circ$ and latitude $0^\circ \pm 3^\circ$. Extension and location are fully compatible with the morphology of the Cygnus X region, and in particular, with the location of the Cyg OB2 cluster.

Using an evolutionary synthesis model, Knödlseder et al. (2002) have suggested that Cyg OB2 is indeed the dominant ^{26}Al source in the Cygnus X region. Yet, actual nucleosynthesis models underestimate the 1809 keV line flux by roughly a factor of 2. Possibly, the neglection of stellar rotation, which plays a crucial role for the evolution of massive stars, may explain this discrepancy.[15]

The SPI measurement provide for the first time an estimate of the intrinsic width of the 1809 keV line in Cygnus X. The measured width corresponds to a Doppler broadening of 550 ± 210 km s^{-1} (FWHM). This translates into expansion velocities of 170-380 km s^{-1} if a thin expanding shell is assumed, or to 240-550 km s^{-1} for a homologously expanding bubble. Obviously, these values significantly exceed expectations (see above), hence it seems unlikely that the gamma-ray data trace expansion motions. Yet, turbulent motions in hot superbubbles can reach velocities of a few 100 km s^{-1} (De Avillez, these proceedings), and the ^{26}Al ejecta may eventually follow these motions. Hence, the gamma-ray observations may provide a direct measure of the turbulent motions in the hot Cygnus X superbubble. However, more observations of Cygnus X are required to confirm this hypothesis, by providing more stringent informations on the ^{26}Al line profile.

4 Conclusions

Multi-wavelength observations reveal that Cygnus X that is a textbook case of a massive star forming region. Its massive (O-type) star population is catalogued using optical and near-infrared photometric and spectroscopic observations, unveiling a young massive central cluster (Cyg OB2), surrounded by even younger embedded star clusters. The youth of Cyg OB2 explains the apparent absence of supernova remnants and the presence of ubiquitous diffuse thermal radio emission, produced by the ionising UV radiation of its O-star members. The observations suggest that the combined stellar winds of the massive Cyg OB2 members have blown a superbubble of $\sim$ 100 pc in diameter into the ISM, compressing the surrounding gas, leading

to triggered star formation near the bubble shell. The superbubble is filled with hot rarified gas that gives rise to soft X-ray emission. The massive stars also ejected already a significant amount of nucleosynthesis products into the bubble, as traced by the 1809 keV gamma-ray line from radioactive ^{26}Al decay. The 1809 keV line shape indicates turbulent velocities of a few 100 km s^{-1} within the bubble that may help to accelerate cosmic rays in this region. The recent discovery of a TeV gamma-ray source in Cyg OB2 together with the presence of an unidentified EGRET gamma-ray source may be a further indication of present cosmic-ray acceleration in Cygnus X.[3]

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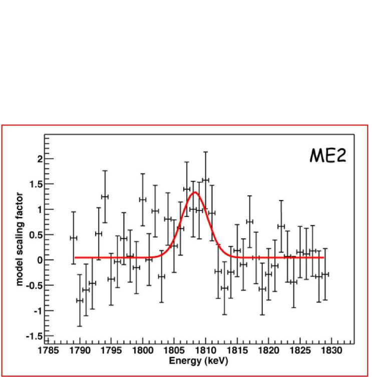
ME2
model scaling factor
Energy (keV)
2
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1
0.5
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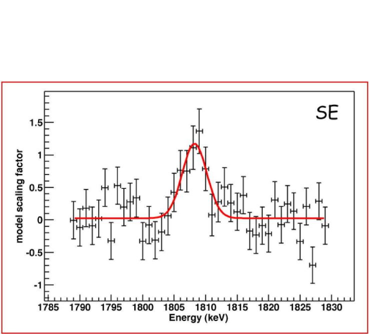
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